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Giotto Navigation Support

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Cooperative efforts between NASA and the European Space Agency (ESA) in supporting the flight of Giotto to Halley's Comet included prelaunch checks of ESA navigation software and delivery of validated DSN radio metric tracking data during the mission. Effects of drag from passing through the coma are seen in data received pre and post encounter. The post encounter Giotto trajectory provides a solar occultation in January 1988, prior to returning to the earth in 1990 for possible retargeting to yet another comet.

I. Introduction

NASA, through the DSN, played a vital role in the navigation of the European Space Agency's (ESA) Giotto spacecraft to Halley's Comet by receiving radio metric tracking data from the spacecraft and transmitting it to the European Space Operation Center (ESOC) in Darmstadt, West Germany. Insuring that ESOC was prepared to use the data for its first deep space mission involved several years of detailed checks of their navigation program. At the same time, communication systems needed to transfer information enabling the DSN to acquire the spacecraft and ultimately return validated radio metric data in a timely fashion to ESOC were defined and checked out.

This report summarizes the checkout procedures used in preparing ESOC software for navigating Giotto with DSN tracking data and describes the flow of information between JPL and ESOC during the mission. Although JPL was not required to provide estimates of the spacecraft encounter, a brief comparison of the ESOC and JPL derived encounter conditions is included. Also shown is evidence of the drag experienced by the spacecraft while passing through the comet's coma.

The mission has not ended. Giotto survived the flyby, not unscathed, but intact enough for retargeting to the earth and perhaps eventually to another comet. In the interim, opportunities to probe the solar corona, including a solar occultation are present. Plans for using VLBI techniques to improve orbit determination and hence the occultation science return, may be tested using Giotto in early 1987.

II. Pre-Flight Navigation Activities

Beginning more than two years before the Giotto launch a series of navigation software workshops were held between JPL and ESOC to define and run test cases to verify that the ESOC orbit determination program could successfully process Giotto radio metric data. The tests concentrated on basic orbit determination functions:

(1) Integration of the spacecraft trajectory and variational equations.

(2) Light time solution, time transformations and polar motion.

(3) Computation of observables and partial derivatives.

(4) Differential correction, covariance matrix and mapping.

These functions were tested using the Voyager 1 trajectory and DSN radio metric data acquired from it when the geometry was similar to the forthcoming Giotto encounter. This tracking data was initially sent to ESOC by magnetic tape and later transmitted over communication lines as tests of the system to be used for sending DSN radio metric data during the mission.

An important part of the software tests involved the choice of a planetary ephemeris. It is not only the source of position and velocity of bodies in the solar system, but also of nutation and precession of the earth and a host of astrodynamical constants such as body masses, the length of the astronomical unit and the speed of light. It defines the coordinate system for the dynamics of the spacecraft flight and dictates the values of station locations required to properly process radio metric observables. The one chosen for Giotto operations and hence these tests was JPL Development Ephemeris (DE) 118, which uses the Earth Mean Equator and Equinox of 1950 reference system. It would be the source of data for all solar system bodies other than Comet Halley, which was of no immediate consequence in these tests.

Serving as a standard of comparison would be the JPL Orbit Determination Program (ODP) (Ref. 1) first used in support of Mariner VI and VII and all space missions tracked by JPL since. The test cases were run on the JPL ODP and compared with the same case run with the ESOC ODP. All the JPL cases were run on a UNIVAC 1100 computer with a double precision word length of 18 decimal digits. ESOC used a SIEMENS computer with 16 decimal digits double precision. For Giotto operations JPL switched to a VAX 780, which has the same word length as the SIEMENS. Tests between the two JPL computers showed no navigation degradation for a Giotto type trajectory due to the shorter word length.

The testing began by matching the integration of the spacecraft trajectory between the JPL and ESOC programs. The reference trajectory was based upon a 2.5 month long Voyager 1 trajectory modified to include large spacecraft maneuvers and non-gravitational accelerations to enhance the detection of any possible differences between the two programs. Good agreement between ESOC and JPL was noted at 1 meter in position and 1.E-5 m/s in velocity at the end of the integration.

Two Voyager 1 Doppler points were selected for use in a detailed computation check. Quantities carefully compared were time transformations, polar motion, light time solution, EME50 station location, antenna corrections, and troposphere modeling. The final agreement obtained for the computed observables was 0.0001 Hz S-band or approximately 0.007 mm/s, which indicated that the ESOC ODP could process DSN radio metric data adequately to support Giotto navigation.

Checking the partial derivatives of the observable with respect to spacecraft state, station locations, and polar motion parameters could not easily be done due to differences in the formulation of the filters of the JPL and ESOC programs. The ESOC program uses a current state filter while JPL uses an epoch state filter. Although it would have been possible to map the JPL partials to coincide with the formulation of the ESOC program, this was not done when good agreement between the programs was obtained in the solution for the spacecraft state programs (noted below).

A more comprehensive test of the ESOC program involved the estimation of spacecraft position and velocity using an eight day span of Voyager data. Differences in the estimates obtained by the two programs were 22 km in position and 20 mm/s in velocity. In view of Giotto navigation accuracy requirements of approximately 100 km (1-sigma), exclusive of errors in the comet ephemeris, these differences were considered acceptable for successful navigation. A portion of the difference might be attributed to data processing techniques. For example, polynomial representation of the data smooths it in a preprocessing step before use in the ESOC ODP. Differences between the epoch state filter used in the JPL ODP and the current state estimator employed in the ESOC program might also be a contributing factor although attempts were made to match the filters as closely as possible.

Mapping tests conducted using the above estimation case, involved only a translation in time without changing coordinate systems. These showed the same type of agreement as noted above. Complete test results are reported in an ESOC document, "Giotto Quality Control Document, Single Tests, Results of Orbit Determination Test Runs on Voyager Data", Document GIO-QCD-3, Issue no. 2, F. Hechler and H. Muller, European Space Agency Operations Center, 15 March 1985.

Another orbit determination test involved a 90-day arc of radio metric data. The data was based upon the geometry of the Giotto-like Voyager 1 trajectory, but for extended software checking purposes used precisely known solar pressure, instantaneous, and finite maneuvers. Also present during the last month was a constant acceleration (gas leak). The data observation model also included troposphere effects and random data noise representative of that expected when the DSN would track Giotto. Since the trajectory was known exactly, it was possible to determine when the correct state had been recovered by the ESOC ODP in runs using intentionally mismodeled a priori spacecraft states and/or non-gravitational force models. The ability to recover the correct spacecraft state was comparable to or better than the agreement obtained in the previous Voyager check.

The results of these tests indicated that ESOC should be able to process DSN radio metric data acquired from Giotto. This was indeed confirmed during the mission when differences of 15 km and 17 mm/s in position and velocity, respectively, were noted between JPL and ESOC reductions of DSN data.

III. Flight Operations Activities

A. Navigation Campaigns

The DSN was available under contract to ESA for supplying radio metric data at pre-arranged times during the Giotto mission. Two week tracking periods comprised primarily of two successive DSN passes per day intermingled with tracking collected at the ESA Deep Space Tracking System (DSTS) were called campaigns. These served to enhance Giotto navigation, primarily during the approach and encounter phase by supplying Doppler and range from northern and southern hemisphere sites. There were two stations in the DSTS, a 15-meter antenna at Carnarvon in western Australia and a 30-meter one at Weilheim in the Federal Republic of Germany.

The first navigation campaign occurred from 15 to 29 September 1985, a period during which there were no spacecraft maneuvers of any kind. DSN radio metric tracking was obtained from the 34-meter stations, DSS 12, 42, and 61, and was transmitted to ESOC once a week using the NASCOM network. Table 1 summarizes some information about this data after processing with the JPL ODP and Fig. 1 shows Doppler residuals obtained from both JPL and ESOC processing and likewise Fig. 2 shows range residuals. The Doppler data were compressed to a 600-second count time. The residuals obtained by the two programs are very similar. Some of the differences may be due to variations in data processing techniques. For example, ESOC weights the range at 10 meters whereas JPL weights it at 1000 meters to reduce sensitivity to unmodeled errors, namely range biases and/or station location errors. ESOC may have also processed all the range data collected, while the JPL analysis restricted the range to one point every one-half hour. Other factors possibly contributing to the small differences include the pre-processing of the tracking data required to change it to a polynomial representation for use in the ESOC ODP.

The marked similarity in results served as another verification of ESOC's ability to process DSN radio metric data, as expected after all the software testing, and established confidence for successful data processing during the critical encounter campaign when DSN data would again be received. Other material presented by ESOC at a navigation workshop following the first campaign included residuals of the combined DSN and DSTS tracking data. To successfully process data from both tracking networks it was necessary to determine the location of the DSTS stations in the coordinate system defined by the planetary ephemeris. Planetary Ephemeris DE 118 had previously been used to determine the locations of the DSN stations thereby enabling ESOC to estimate the DSTS locations while holding the DSN locations fixed. These locations were then used for the rest of the mission, which would be especially significant during the encounter campaign when radio metric data from the two networks would again be combined for determining the orbit and designing the final trajectory correction maneuver for a successful encounter.

The second navigation campaign, supporting the encounter, occurred from 1 to 12 March 1986 in which DSTS radio metric data were again augmented with daily DSN radio metric tracking obtained from the 34-meter stations, DSS 12 and 42, and the 64-meter stations, DSS 14 and 63. At the end of a day's tracking, data were validated with the JPL ODP and transmitted via NASCOM to ESOC. Minimal comparison of ESOC and JPL data analysis occurred due to the high activity associated with this phase of the mission. A change in the spacecraft transponder configuration implemented much earlier in the cruise phase caused the received 2-GHz (S-band) signal to be retransmitted at 8.5 GHz (X band). Table 2 shows a summary of the JPL processing of the DSN data taken during this campaign. The noise of the Doppler appears higher than for the first campaign due to two passes of 60-second count time data that could not be compressed. Figures 3 and 4 show plots of the two-way Doppler and range residuals obtained with the JPL ODP.

There was not a requirement for the exchange of navigation results between JPL and ESOC during either of the campaigns. The exchange following the first campaign occurred several months afterwards and served only as a final check of ESOC's ability to successfully process DSN and DSTS radio metric data. The DSN data taken during the encounter campaign aided ESOC in estimating the trajectory of the spacecraft, now that daily attitude maneuvers were occurring, in preparation for the design of the final trajectory correction maneuver. The last DSN pass of this campaign followed that maneuver and helped provide verification of the achieved trajectory change.

B. Navigation Campaign Data Processing

Several interfaces were required between JPL and ESOC in order for the DSN to successfully track Giotto and transmit validated tracking data to ESOC. One of the unique features of the system devised was the capability to directly access data stored in the operations computer at ESOC from JPL.

DSN antenna pointing predicts, required to acquire the spacecraft signal, were generated from a Giotto trajectory integrated by the JPL ODP using initial conditions and solar pressure model obtained from a file in the ESOC computer. Although the conditions in this file were updated weekly, it was not necessary to actually update the predicts very often. In spite of daily attitude maneuvers and the final pre-encounter trajectory correction maneuver, analysis with these current states indicated that predicts generated from a December 11, 1985 state and solar pressure model were adequate to support the project throughout the remainder of the mission, including the encounter phase.

Validation of the DSN radio metric tracking data was performed using a Giotto trajectory generated from a current state and maneuver information obtained from ESOC computer files. The tracking data were prepared by compressing the Doppler to an ESOC specified count time and verifying the use of the correct station and spacecraft hardware delays for the range data. The JPL ODP was then used to validate the data, noting any blunder points to remove before transmission to ESOC.

The NASA Communications Network, NASCOM, was used as part of a communications network to transmit the validated data from JPL to ESOC where it was routed to the operations computer for use in navigation.

C. Encounter Estimate

An estimate of the spacecraft arrival time and position at Halley was derived at JPL from DSN radio metric data collected during the second campaign. Although there was no requirement to deliver these estimates to ESOC, this was done for our own information and then compared with the value obtained by ESOC. Due to the many facets associated with the daily attitude maneuvers and possibly other information known only at ESOC about the attitude behaviour of the spacecraft, one might not expect close agreement between the two solutions. Cause for disagreement in the solutions could also easily come from differences in the comet ephemerides used.

The JPL solutions were obtained with a simple least-squares batch filter, while modeling the maneuvers using data from the ESOC maneuver file. After examining the effects of estimating various sets of the daily attitude maneuvers and the trajectory correction maneuver (TCM), which occurred on 12 March around 01:30 UT, in combination with different a priori uncertainties, the choice was made to estimate 10 of the 12 daily maneuvers with an a priori uncertainty of 10 cm/sec and the TCM with an a priori uncertainty of 50 cm/sec. Data statistics for the residuals obtained from this solution are those shown previously in Table 2. JPL Planetary ephemeris DE 118 and the International Halley Watch comet ephemeris HL47 were used. This Halley ephemeris is derived from earth-based observations ending 24 March 1986 and includes a center of light center of mass offset. The gravitational effect of the comet on the trajectory of the spacecraft was ignored. The analysis used the consider option to augment the covariance of the estimated spacecraft position for the effects of possible errors in the tracking station locations of 2 meters in distance from the spin axis, 3.0 E-5 degrees (approximately 3 meters) in longitude, and 20 meters in distance from the equator plane.

A predicted comet miss distance of 610 km with an uncertainty of 104 km was obtained. Augmenting this uncertainty for the assumed station location errors resulted in an uncertainty of 138 km. The predicted time of closest approach is 14 March 1986, $0^h\ 2^m\ 58.5^s$ UTC with an uncertainty of 0.8 s which grows to 1.1 s with the consider parameters.

Analysis by ESOC (Ref. 2) using both pre and post encounter DSN and DSTS radio metric data and their comet ephemeris derived from Earth-based observations augmented with the Vega-1 and Vega-2 Halley observations also indicates that the actual miss distance was 610 km with an uncertainty of 40 km with a time of closest approach of $0^h\ 3^m\ 0.4^s$ UTC.

D. Passing Through the Halley Coma

A drag effect attributed to Giotto passing through the comet's coma can be observed in pre and post encounter two-way DSN radio metric data. Figures 5 and 6 show changes in Doppler and range residuals obtained when an ESOC provided post TCM Giotto state was integrated forward and used to form residuals. The first post encounter data was obtained about 12 hours after closest approach and shows an offset of 9.4 Hz, X-band or 171 mm/sec in the Doppler, Fig. 5. This is independently confirmed from the slope in the post encounter DSS 14 range data, Fig. 6, which yields similar velocity change of 168 mm/s. (There was no pre-encounter range taken following the TCM.) A value for the total reduction in the spacecraft velocity can then be computed knowing that the earth direction is 44.2 deg from the velocity vector. The value derived for the total velocity, 238.5 mm/sec, agrees to within 4 mm/s with estimates made by T. A. Morley at ESOC from DSTS two-way tracking ("Braking Effect of Dust Impacts on GIOTTO at Encounter," T. A. Morley, European Space Operations Centre, 18 March 1986). Simple assumptions of inelastic impacts along the velocity vector and the conservation of momentum infer the total mass of the impact dust to be 2.0 grams. This is obtained assuming the velocity of the impacting dust to be 68.377 km/s and using the ESOC value (Morley) for the spacecraft mass of 573.886 kg. More thorough analysis by Morley using longer spans of DSN and DSTS pre and post encounter two-way radio metric data gave an estimate of 1.9 g.

Analysis of this same data by the Giotto Radio Science Team reported in Ref. 3 indicates that large uncertainties in the momentum multiplication factor arising from enhanced momentum transfer due to inelastic high-energy particle impacts reduces the total mass of the impacting dust to the 0.1–1 g. range.

The two-way radio metric data analyzed above was collected several hours either side of encounter and therefore cannot be used to probe the nature of the coma itself. One-way Doppler received throughout the encounter period, could be used for studies of the coma, but requires substantial analysis to extract meaningful information. Figure 7 shows three minutes of this data recorded at DSS 43. Some signatures in this data correspond with known particle impacts, but cycle slips are most certainly present and lock was lost during this interval. These all probably invalidate the large offset of approximately 17 Hz observed pre and post encounter. This offset is about a factor of four greater than the effect observed in the two-way Doppler discussed above which indicates the need for careful interpretation of this data. It appears that if any information about the coma is to be gleened from the one-way data, it will require analysis of the open loop recordings, a task which is currently underway. One-way observations at Carnarvon and Parkes, Australia reveal similar signatures. There do not appear to be any plans to continue the analysis of these data.

IV. Post Encounter Trajectory and Possible Future Activities

Following the encounter a series of spacecraft maneuvers were performed which placed Giotto in a trajectory which would fly by the earth at about 20,000 km in July 1990 for subsequent retargeting to another comet. Following these maneuvers, daily communication from the DSTS to Giotto ceased, DSN communication having previously ended following the DSS 14 pass on 14 March. Giotto is in a hibernation state with only occasional communications planned (Ref. 4). The resulting trajectory contains an extended period of some 150 days during which the angular separation of Giotto and the sun will be less than 10 solar radii climaxing with a 5 day solar occultation in January 1988. Figure 8 shows Giotto relative to the sun during this 150-day period in a coordinate frame in which the trace of the Giotto trajectory as seen from the earth is plotted in a plane located at the sun and perpendicular to the fixed earth-sun line. The axes of the plot show the angular separation in right ascension and declination of the spacecraft from the sun. A perspective of the trajectory throughout the entire hibernation period can be seen in Fig. 9 in the same type of a plot. The horizontal axis, which serves as an approximate sun-earth-Giotto angle, indicates that Giotto is always within 70 deg of the earth-sun direction.

Two additional plots of general interest are the geocentric declination, Fig. 10 and right ascension, Fig. 11, covering the time span November 1986 to June 1988. Note that the solar occultation occurs near –23 deg declination while the June solar graze occurs at about +23 declination.

In anticipation of the interest surrounding the solar occultation and the need for accurate orbit determination in the presence of fairly frequent maneuvers, a VLBI experiment using Giotto is being studied for early 1987. Preliminary analysis indicates that this data combined with conventional radio metric observables can be very effective in determining the orbit in this environment. Results of this proposed experiment should be of interest to the Ulysses project which uses the same radio transponder and will be probing the solar environment also.

References

1. Moyer, T. D., *Mathematical Formulation of the Double-Precision Orbit Determination Program (DPODP)*, Technical Report 32-1527, Jet Propulsion Laboratory, Pasadena, Calif., May 15, 1971.

2. Munch, R. E., Sagdeev, R. Z., and Jordan, J. F., "Pathfinder: Accuracy Improvement of Comet Halley Trajectory for Giotto Navigation," *Nature*, Vol. 321, No. 6067, pp. 318–320, 15 May 1986.

3. Edenhofer, P., Bird, M. K., Brenkle, J. P., et al., "First Results From the Giotto Radio-Science Experiment," *Nature*, Vol. 321, No. 6067, pp. 15–21, May 1986.

4. Morley, T. A., and Hechler, F., "GIOTTO, Orbit Prediction During Giotto Hibernation," European Space Operations Centre, *GIOTTO Study Notes*, No. 60, April 1986.

Table 1. DSN data summary for Campaign #1

A. Amount of Tracking Data Processed

Data Type	Number of Points			From	To
	Received	Used	% Used		
Doppler (F2)	532	532	100	15 Sept 20:59	29 Sept 11:51
Range (PLOP)	511	139	27	15 Sept 20:53 (Actual amount used reduced to facilitate processing.)	29 Sept 11:44

B. Total Amount of Tracking Data Received

Station ID	Data Type	Band[a]	Points
DSS 12	F2	S	138
DSS 42	F2	S	303
DSS 61	F2	S	91
DSS 12	PLOP	S	139
DSS 42	PLOP	S	298
DSS 61	PLOP	S	74

[a]S = 2 GHz

C. Data Statistics and Weights

Data Type	Residuals		Data Weight
	Bias	Sigma	
Doppler (F2)	0.00001 mm/s	0.074 mm/s	1 mm/s (60 s count)
Range (Plop)	0.50 m	25 m	1000 m

Table 2. DSN data summary for Campaign #2

A. Tracking Data Received

Data Type	Number of Points			From	To
	Received	Used	% Used		
Doppler (F2)	1008	955	95	1 March 12:46	12 March 18:52
Range (PLOP)	133	131	98	1 March 13:43	11 March 12:08

B. Total Amount of Tracking Data Received

Station	Data Type	Band[a]	# Points
DSS 12	F2	S/X	792
DSS 14	F2	S/X	36
DSS 42	F2	S/X	96
DSS 63	F2	S/X	31
DSS 12	PLOP	S/X	86
DSS 42	PLOP	S/X	36
DSS 63	PLOP	S/X	9

[a]S = 2 GHz; X = 8.5 GHz

C. Data Statistics and Weights

Data Type	Residuals		Data Weight
	Bias	Sigma	
Doppler (F2)	0.00089	0.30 mm/s	1 mm/s (.055 Hz)
Range (PLOP)	−0.095	29 m	1000 m

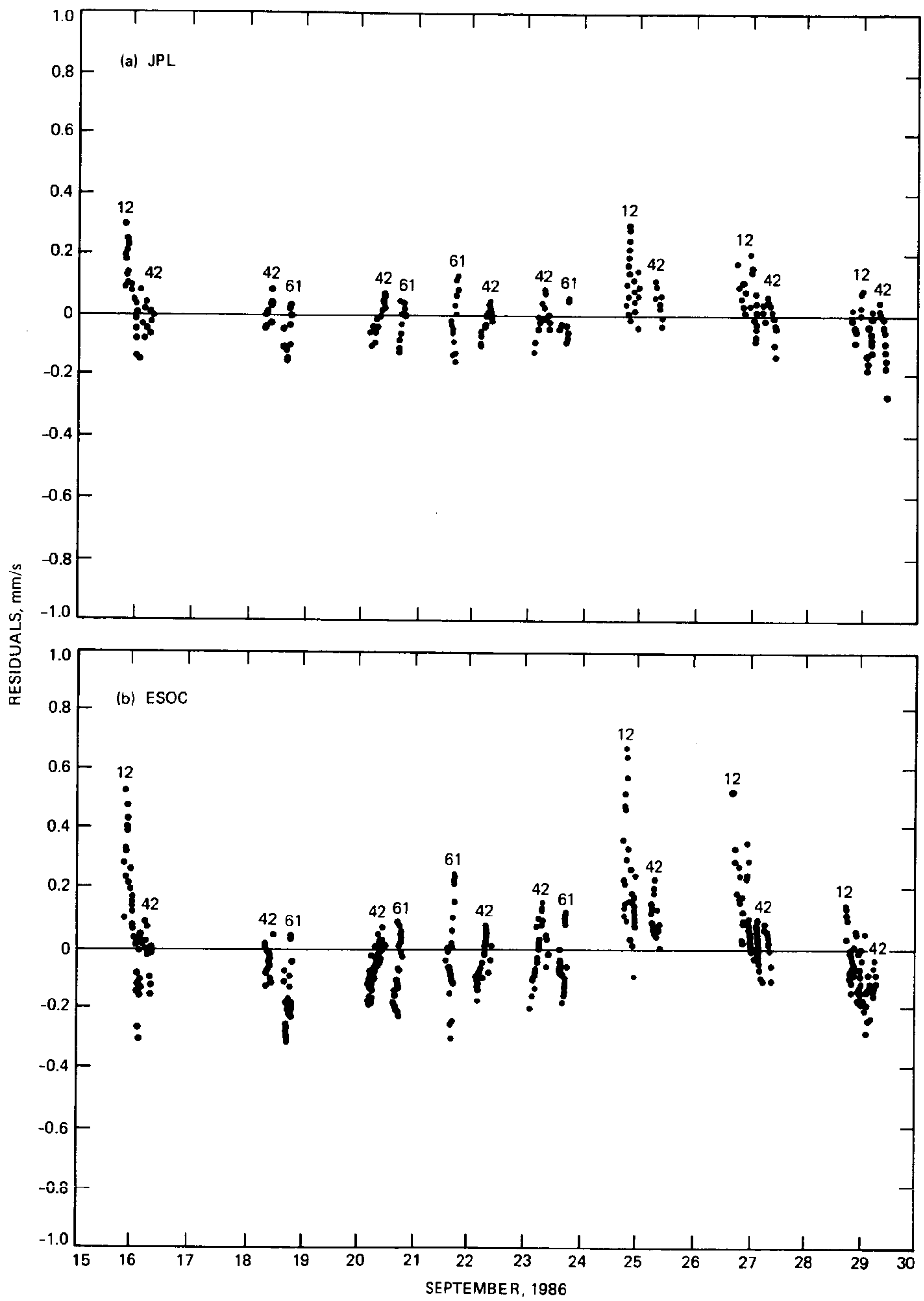

Fig. 1. JPL and ESOC DSN Doppler residuals from Campaign #1

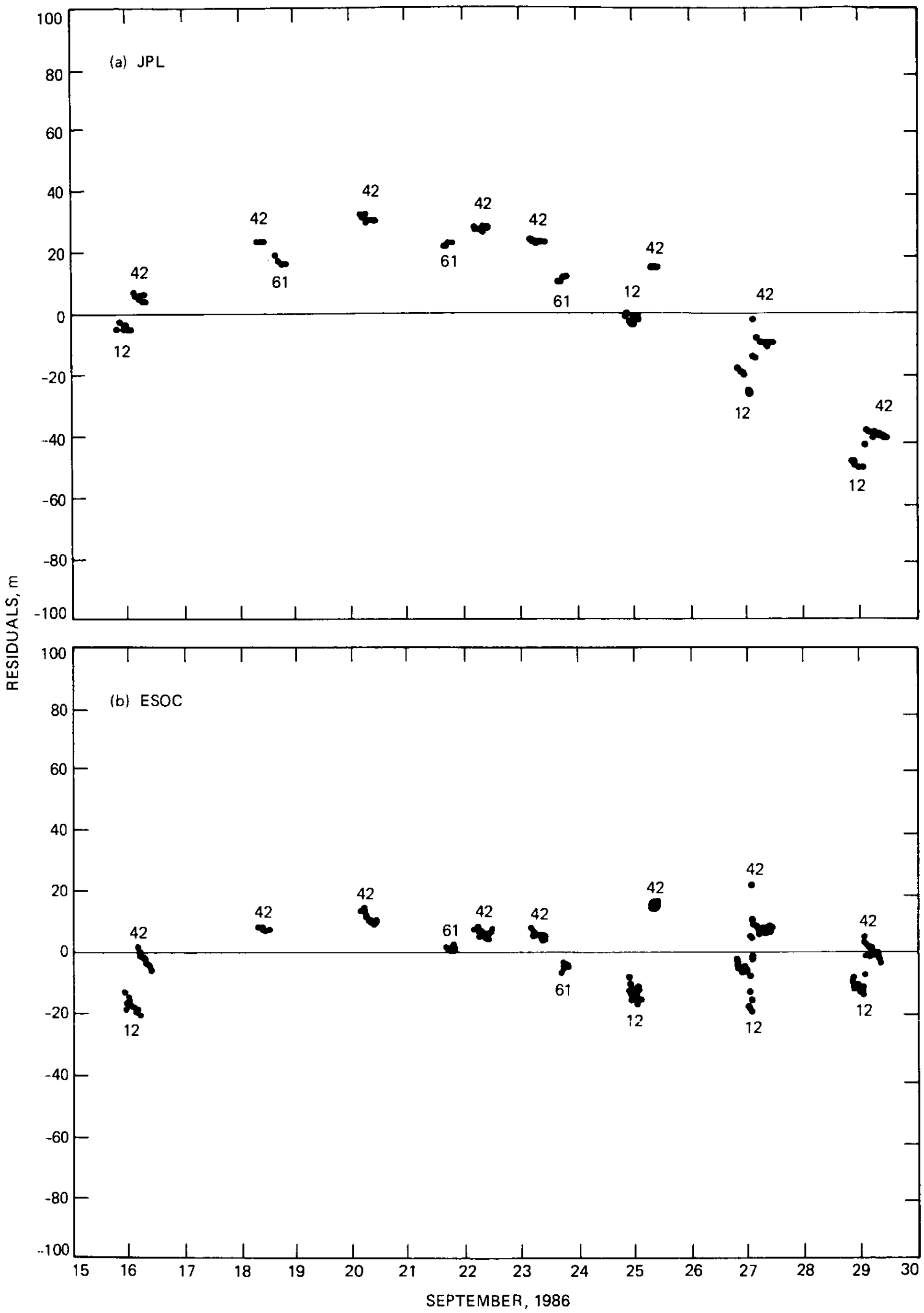

Fig. 2. JPL and ESOC DSN range residuals from Campaign #1

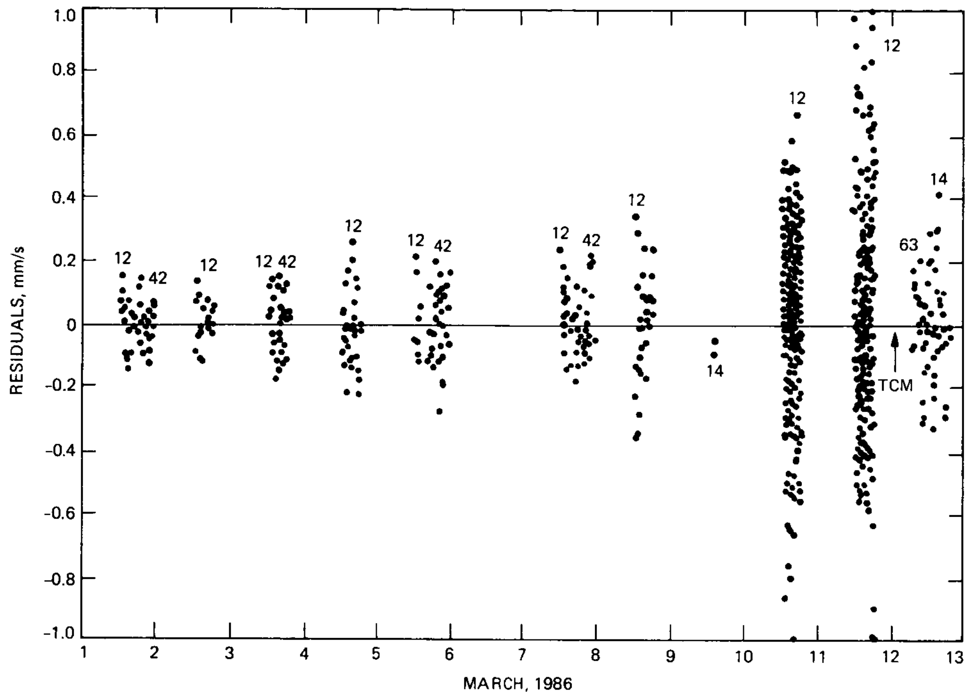

Fig. 3. JPL DSN Doppler residuals from Campaign #2

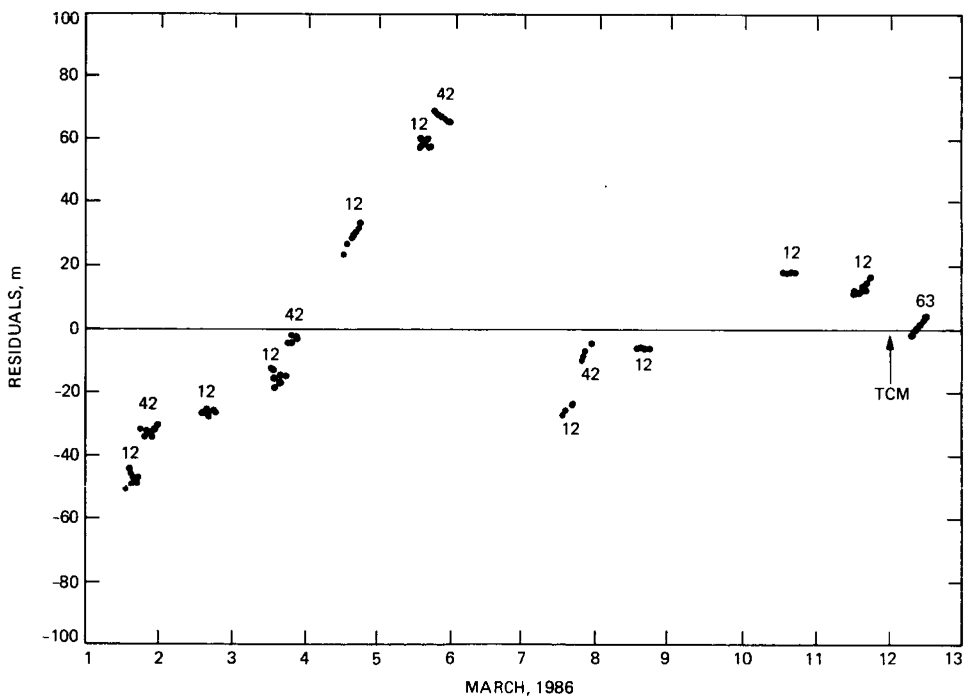

Fig. 4. JPL DSN range residuals from Campaign #2

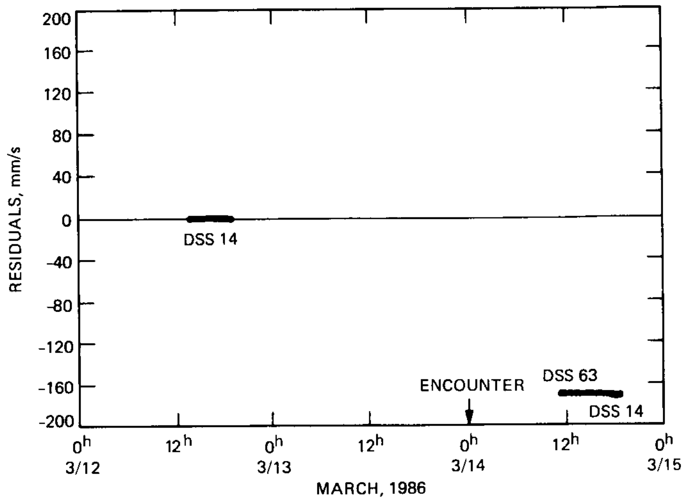

Fig. 5. Post encounter velocity change observed in Doppler residuals

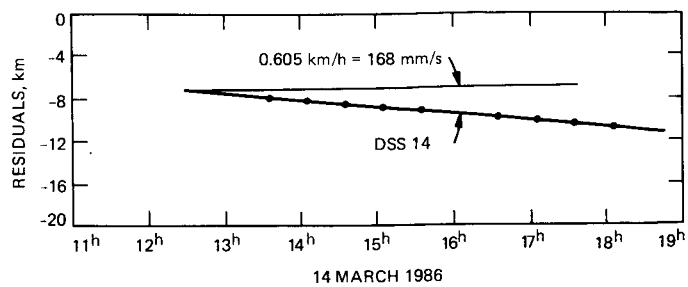

Fig. 6. Post encounter velocity change inferred from range residuals

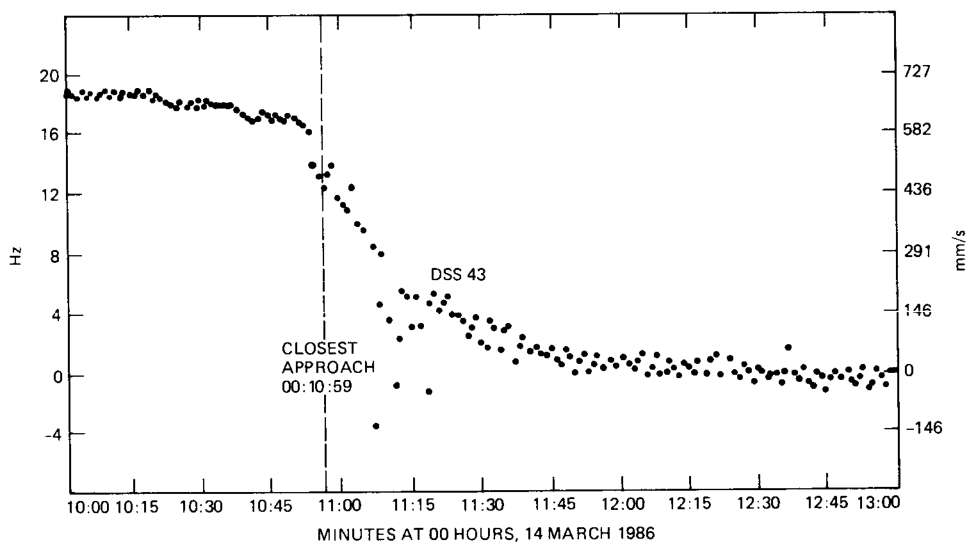

Fig. 7. DSN Giotto encounter one-way Doppler residuals, 1-second count time

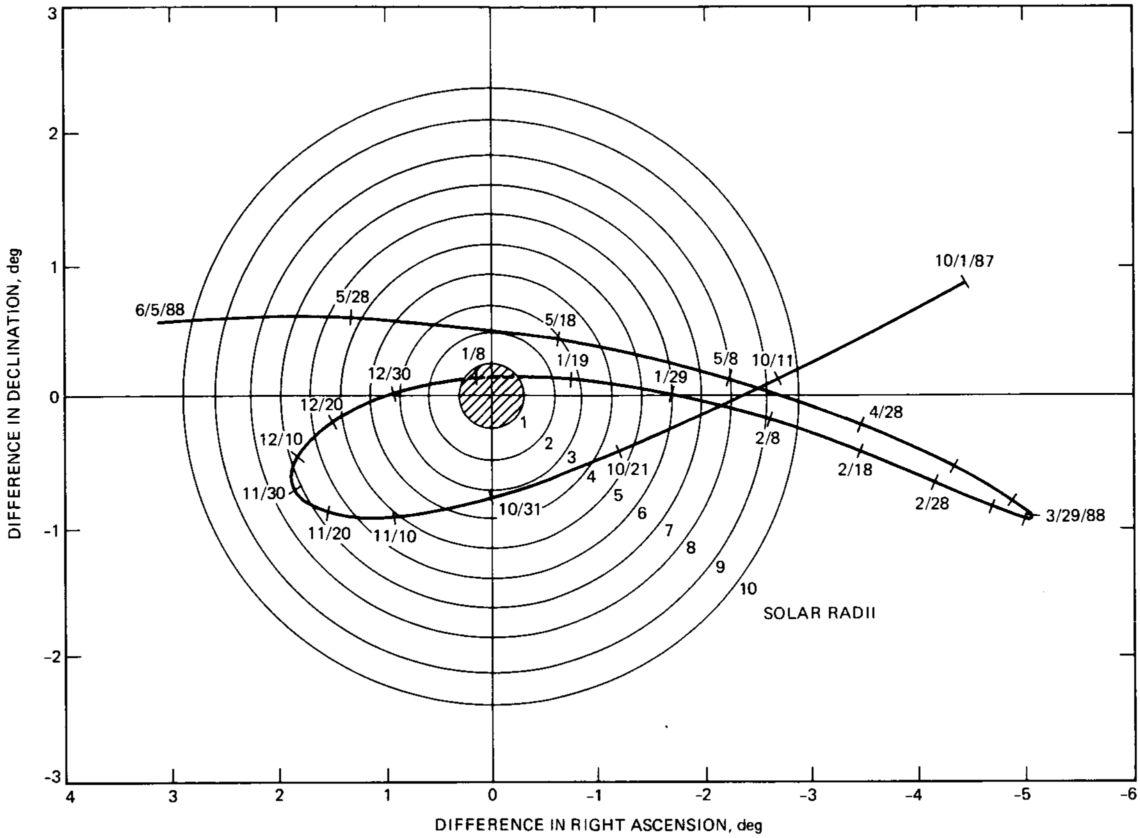

Fig. 8. Giotto relative to Sun October 1987 to June 1988

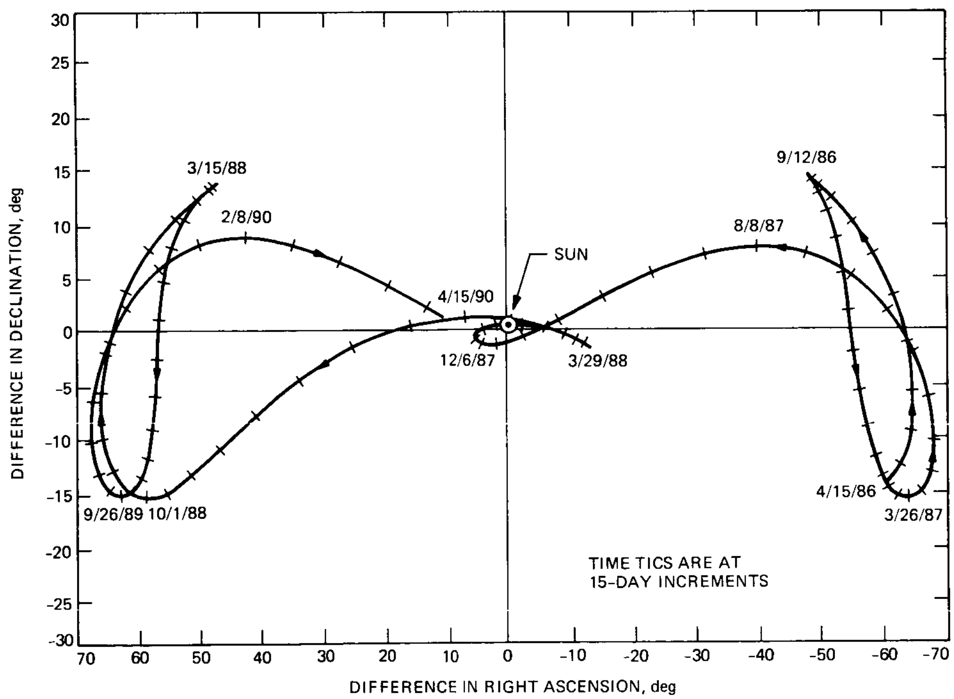

Fig. 9. Giotto relative to Sun April 1986 to April 1990

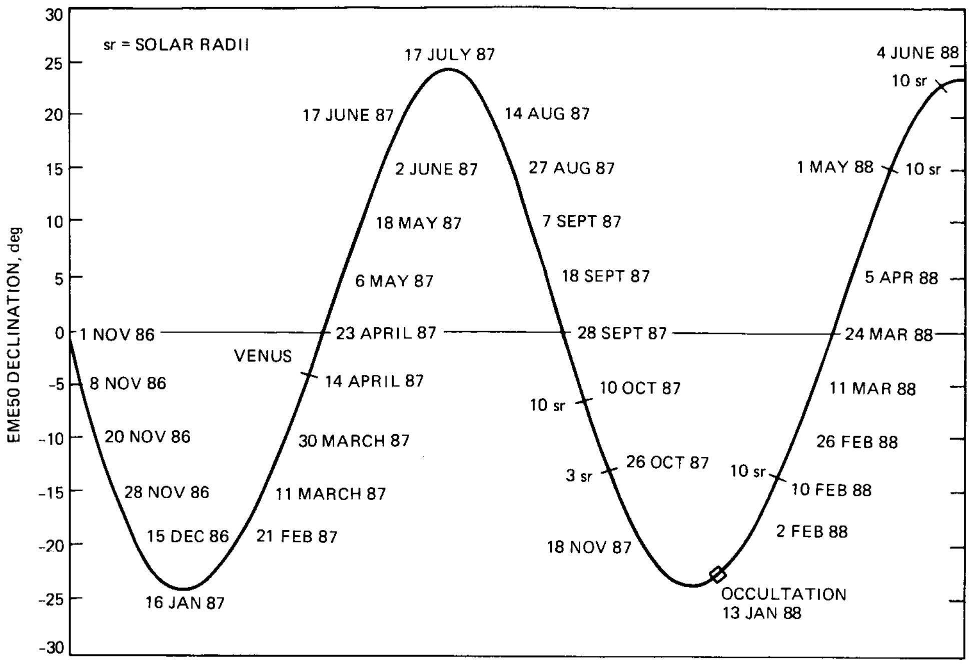

Fig. 10. Giotto EME50 declination November 1986 to June 1988

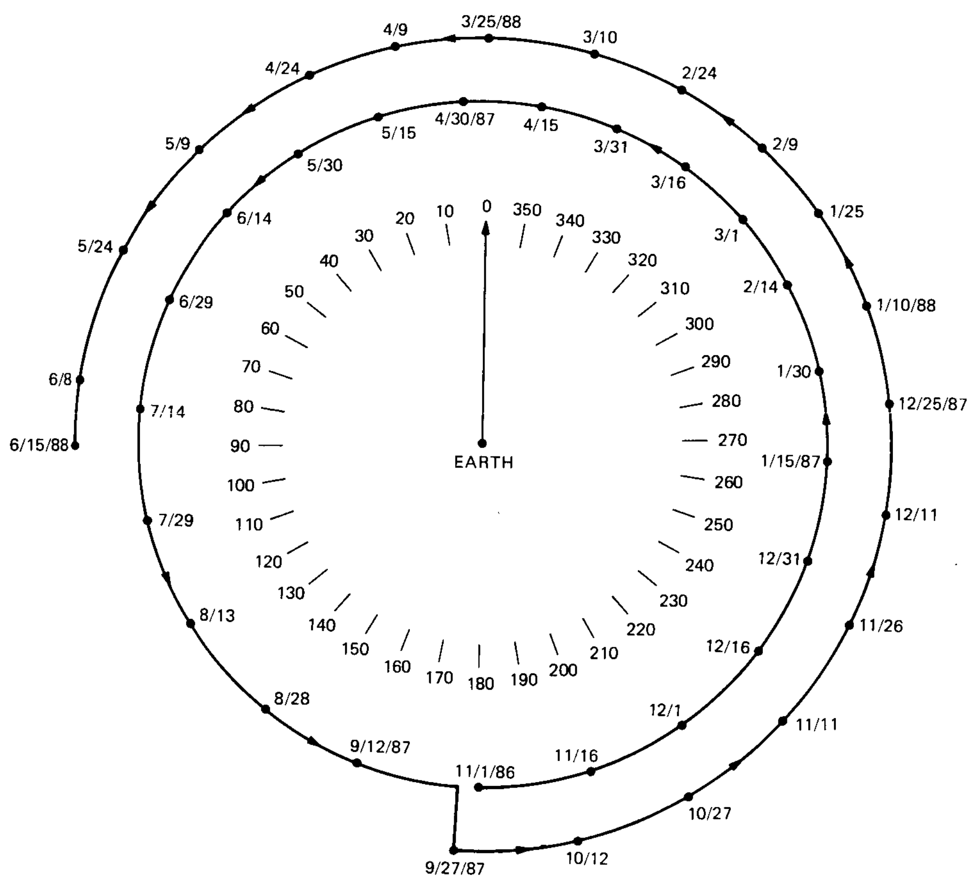

Fig. 11. Giotto EME50 right ascension November 1986 to June 1988